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# Evaluation of two cooling devices for construction workers by a thermal manikin

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**Abstract**
Two kinds of wearable cooling devices were evaluated for their cooling effect by a thermal manikin. All measurements were conducted in a climatic chamber. The cooling fans worked almost 3 h. Their cooling effect was large at the head and had little effects on other parts of the manikin. They decreased the insulation of a typical clothing ensemble of outdoor workers in construction industries from 0.75 clo to 0.48 clo. The cooling vest for heat protective clothing mainly worked on the trunk. It did not have enough effect nor had steady cooling effect. But the vest worked as direct cooling device for the trunk. The effect of the fans to Standard Effective Temperature (SET) is evaluated by simulation. The difference of SETs between the case of the typical ensemble and the case with the cooling fans at 35 °C of the surrounding environment is 2.6 °C. The lower the surrounding temperature is, the larger the difference between SETs of different clothing insulation value is.

## Introduction

Climatic conditions in Japan vary much. It is hot and humid in summer, but cold and dry in winter around the central part of it. There are many cases of heatstroke in summer due to the climatic condition, which leads to management for environmental condition by WBGT and education on health condition for outdoor workers (The ministry of health, labour and welfare of Japan, 2016). Prevention of heatstroke is important in the view point of industrial safety and productivity. Workers in construction sites have to wear long-sleeve shirts, long-trousers and helmets especially for safety reason and there are many cases of heat stroke in summer.

There have been many studies about workers' health and productivity in hot environment. Chan and Yi (2016) summarized the current status of them. It said that six parameters (ambient temperature, relative humidity, radiant temperature, air velocity, metabolic rate and clothing properties) had to be included to evaluate the heat stress but one of empirical indices, WBGT, was used most widely. It also said that uniforms for workers exposed to heat stress could be considered in relation to the balance between the effect of heat stress and protection from the hazards on the job. According to this study, there were three types of cooling garments had been used by athletes and soldiers, which were liquid cooling garments, air cooling garments and garments with phase change materials (PCMs). It is also pointed out that workers often disliked wearing those

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cooling garments unfortunately because of several reasons like weak cooling capacity, short cooling duration and inflexibility.

There are many studies on cooling garments with PCMs. Shim et al. (2001) incorporated microcapsules of paraffin into the structure of forms and coated the form onto fabrics. The cooling effect lasted for 15 min and the average cooling effects was 11.0 W at most for that period. Smolander et al. (2004) conducted the experiments to investigate physiological and subjective responses in fire fighters wearing 1 kg ice vest under standard clothing for fire fighters. Heart rate was 10 beats/min lower on average and the amount of sweating was reduced by 13% with ice vest. Subjective sensations of effort and warmth were lower during work with the ice vest than the work without it. It concluded that the ice vest reduced physiological and subjective strain responses during heavy work in the heat. Gao et al. (2009) conducted the experiments of PCMs, sodium sulphate decahydrate, with Swedish firefighting ensembles. The melting temperatures of PCMs were 24 and 28 °C. The subject walked on the treadmill of 5 km/h for 30 min at longest at 55 °C and RH 30% after simulating preparation work. PCM with the melting temperature of 24 °C had more effective cooling effect than 28 °C. It concluded that the temperature gradient between skin temperature and PCM melting temperature was important to get effective cooling effects.

Many research on air cooling garments utilized ventilation units (fans) placed in clothing fabrics. Zhao et al. (2013) conducted the experiments with a sweating thermal manikin wearing short-sleeve clothing. The clothing had two fans and closable openings. The testing environment was 34 °C and RH 60%. The location of fans and openings affected the heat loss from the torso, which varied from 137 to 251% in the view point of increment compared with fans-off condition. When the fans were placed at the zone where it had an opening, the corresponding zone was the best cooled. The location of ventilation brought significant difference in localized intra-torso cooling among the various conditions. It concluded that neither the ventilation location nor the opening design had significant differences in total torso cooling. Lu et al. (2015) conducted the experiment of the combined cooling effects by PCMs and fans with a sweating manikin. The environment condition were hot and humid (34 °C and RH 75%) and hot and dry (34 °C and RH 28%). The fans produced a constant cooling power of 108 W and 320 W for the whole body respectively in both conditions for the experiment period of 3 h. But the addition of PCMs provides a limited duration of cooling, 70 min at longest and the cooling time depends on test conditions.

In the practical view point to construction industries, Chan et al. (2015) investigated the effect of a cooling vest in four industries, including construction, horticulture, outdoor cleaning, airport apron, and catering and kitchen during summer days in Hong Kong. The cooling vest in the research was commercially available and had two cooling fans and three cooling gel packs. Each worker participated in this investigation experienced 2 h routine in the environment with WBGT varying from 26 to 36 °C. The physiological and subjective responses were measured before and after the routine and compared. The workers of the construction industry gave the lowest scores of physiological and most of subjective response. But the physiological burden itself was reduced. Yi and Chan (2013) studied to improve the productivity and to reduce the problem of heat stress with the different view point from cooling garments. They conducted the research to optimize the work and rest schedule for construction rebar workers in hot and humid environment. To optimize the schedule, they conducted the field studies during the summer time in Hong Kong at first. They used Monte Carlo simulation technique to account for the uncertainties and variations in the field study. The study proposed the different time schedule to the morning with low WBGT and to the afternoon with high WBGT.

There are several indices for heat stress. Brake and Bates (2002) said they were divided into two categories. Empirical indices have been developed from field measurements, like WBGT, and the heat stress limitation is expressed by environmental parameters. The other one, rational indices are based on heat balance of human body. The study showed the limiting metabolic rates (the upper limit of metabolic rate) were different to each index even in the same environment. There are several models to treat the heat balance on human body. The two-node model of human body was proposed by Gagge et al. of Yale University in 1972 (Parsons 2003). Standard effective temperature (SET) is calculated by the model and is a comprehensive index for thermal stress based on, considering air temperature, radiant temperature, air velocity, humidity, clothing insulation and metabolic rate.

It seems important for cooling devices used in construction industry not to prevent workers' movement and to supply sufficient cooling effect. From this point, the property to be easily attachable and detachable from workers' bodies is suitable for the industry. The existing research has been mainly concerned on the cooling effect by those devices and has not considered much on this aspect. The cooling devices with those properties should be evaluated for this purpose. This paper aims to investigate the cooling effect of two wearable cooling devices for construction industry by a thermal manikin. One device utilizes fans and the other does PCMs. The cooling effect is expressed as the increment of heat loss and also in terms of time duration because the workers usually work for several hours continuously. The cooling effect is evaluated by SET.

## Method

### Cooling devices

The first device utilizes cooling fans (expressed FANS in this paper). Two fans are placed with ducts of plastic pipes in wearable harness (Fig. 1a). The weight is 700 g. FANS is located on the back and is intended not to be obstacles for body movement. It is detachable easily. There are three air outlets on the duct with the area of 1.5 $cm^2$ for one outlet (Fig. 2a). The ends of the ducts were plugged. Fans are operated by rechargeable batteries and the volume of supplied air is estimated about 10 $m^3$/h for one fan by measurements. Discharged air from the outlets mainly cools face and neck, bare parts of the body (Fig. 2b). The cooling effect is caused by high air velocity around the body, which leads to high convective heat transfer coefficients. It is effective both to sensible heat loss and to latent heat loss.

The second device is a cooling vest with PCMs (VEST, Fig. 1b). There are two kinds of phase change materials in this study. One is gels with water (referred to as ICE in this paper), which changes from solid to gel at 0 °C. The other is sodium sulfate, which changes from solid to gel at 28 °C (referred to as PCM). There are 11 pockets on the inner surface of VEST (Fig. 3) and each pocket can contains one or two cooling bags of PCMS. The weight of VEST with 22 bags is 2.5 kg. Those bags cool down the body

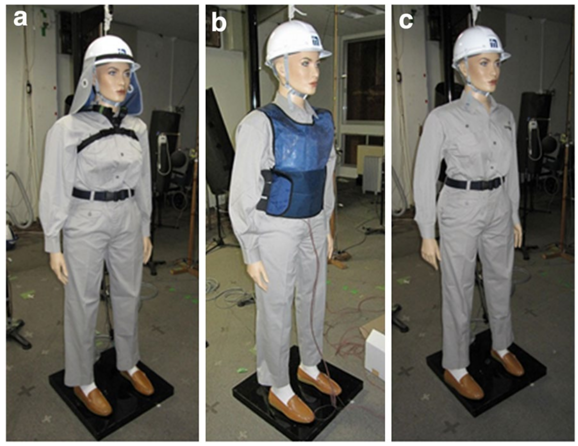


**Fig. 1** Device setting for measurement. **a** FANS, **b** VEST, **c** REF

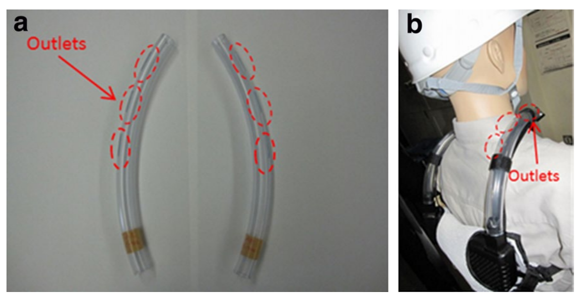


**Fig. 2** Details of FANS. **a** Location of outlets, **b** placement of FANS to manikin

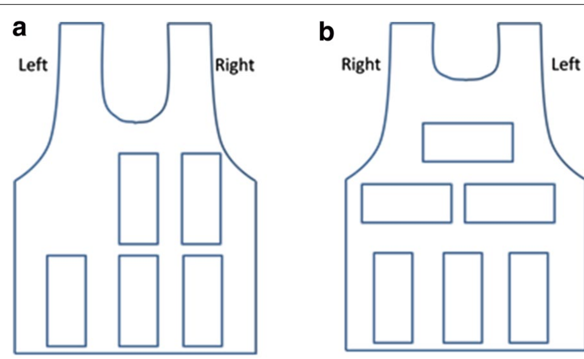


**Fig. 3** Placement of pockets for VEST (inner view). **a** Front, **b** rear

mainly by direct contact and they work for sensible heat loss. VEST is mainly used to cool down the inner temperature of heat protective clothing in high temperature such as worn by fire fighters. The purpose of the measurement is the evaluation of effectiveness when used as the outer ware for construction workers.

## Thermal manikin

Cooling devices mentioned above are effective to local parts of the body. The thermal effects by them have to be evaluated locally and for the whole body. A thermal manikin with 20 segments (Nimatic, Denmark) was used for the measurements. The shape of the manikin is an average Danish woman (Fig. 4). The height is 1.68 m and the total surface area is 1.483 $m^2$. Temperature and heat loss for each segment are measured independently every one minute.

The material of the manikin's temperature sensors is nickel. It is commonly used for temperature measurement. The manufacturer of the manikin recommends the calibration temperature with two levels, the lower temperature and the higher temperature. The manufacturer describes 20 and 30 °C as a set of example for calibration. The manikin was calibrated at 20 and 35 °C prior to the measurements for the evaluation. The higher calibration temperature of 35 °C was selected because the segment temperatures in the measurements were expected to rise to higher than 30 °C.

There are three logics for controlling the manikin. The first is constant temperature for each segment. The second is constant heat loss for each segment. The third is comfort control, which controls the relationship between the temperature and the heat loss for each segment by Eq. 1 (Tanabe et al. 1994). Comfort control was used when the measurements were carried out for the evaluation. In the measurements, temperatures and heat losses of each segment of the manikin were measured every 60 s.

$$t_{s,i} = 36.4 - 0.054Q_{t,i} \quad (1)$$

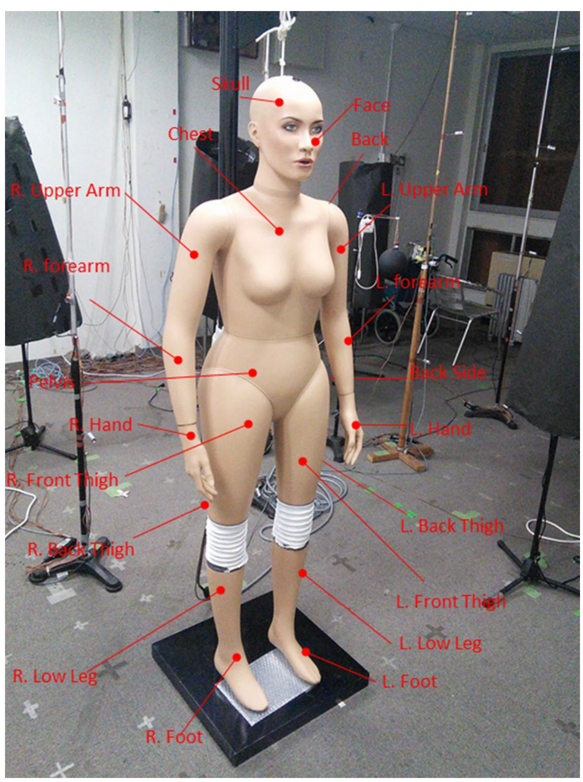


**Fig. 4** Constitution of manikin segments

$t_s$: surface temperature of thermal manikin [°C], $Q_t$: sensible heat loss from the surface of manikin [W/m$^2$], (Subscript i stands for body segment).

## Climatic chamber

All the measurements were conducted in a climate chamber which has an inner room and five outer rooms. The inner room's floor area is 40.5 m$^2$ and its ceiling height is 2.8 m. Each room has its own air-conditioning system and temperatures in them are controlled independently. The air-conditioning systems for outer rooms, not the inner room, were operated for the measurements. As a result, the temperature of inner room was close to the average of the outer rooms and the air velocity was very low (less than 0.05 m/s) in the inner room. The manikin was located in the inner room and it was not affected by the air movement from the air-conditioning system of the inner room.

## Protocol for evaluating FANS

As mentioned before, FANS changes the convective heat transfer coefficient around the body, which affects the sensible heat loss and the latent heat loss from the human body. The manikin used only simulates the sensible heat loss and it is difficult to evaluate the latent heat loss directly. To solve this problem, nominal change of clothing insulation was evaluated. There were evaluations for two clothing insulation. One was a typical clothing ensemble for outdoor workers in construction industry, which is referred to as REF (control). The other was REF with FANS. The temperature in the chamber was set to 25 °C for both measurements. The manikin was kept in the chamber at least 12 h before stating the measurement and had reached to steady state. The measurement was continued for 3 h after reaching at the steady state for REF but terminated for FANS when the fans stopped because of the end of power supplied by batteries.

Clothing insulations were evaluated at the temperature of 25 °C. The clothing insulation was calculated from the average value of the last 60 min. The clothing area factor was estimated by Eq. 2 (ASHRAE 2013).

$$f_{cl} = 1.0 + 0.3I_{cl} \tag{2}$$

$f_{cl}$: clothing surface area [-], $I_{cl}$: intrinsic clothing insulation [clo].

## Protocol for evaluating VEST

As mentioned before, VEST is worn usually in heat protective clothing for workers in high temperature. Outdoor workers in construction sites don't wear the protective clothing, so the vest would be worn on the daily clothing. All of heat absorption by cooling bags would not contribute to cool down the body when used in such ways. It is important to evaluate the cooling effect itself and the effective time period. The surrounding temperature was set to 31 °C. This temperature is selected to simulate the summer condition in Japan. 31 °C is not the highest temperature but is experienced daily in Japan. The manikin had reached to steady state before starting the measurement, similar to the evaluation of VEST. There was little dew condensation on cooling bags because the absolute humidity in the chamber was low without humidification. As there were two kinds of cooling bags for VEST (ICE and PCM), there were four possible combinations for the measurements. Selected cases for the measurement were PCM only (PCM), ICE only (ICE), combination of PCM for inner side and ICE for outer side (PCM + ICE).

## Results

Table 1 summarized the measurement conditions for REF, FANS and VEST with surrounding temperatures. The distance of the measurement points of the ambient temperatures from the manikin was about 1 m. For all the measurements, the temperature in the chamber was controlled well around the set point. Both devices had specific segments cooled effectively. The measurement results are divided into two groups; one is affected, the other is others. Area weighted temperature and heat loss were calculated for each group.

### Effect of FANS

The cooling effect was large at the face and the scull and had little effects for other segments. FANS worked almost 3 h (Fig. 5). The effect was almost constant after 30 min and lasted for about 3 h. The flow rate became constant immediately when turning on FANS, which means the unstable condition in the first 30 min was caused by the characteristics of the manikin itself. Before the measurement, the heat losses were 46.1 W/m$^2$ in affected segments and 41.8 W/m$^2$ in the other area (Fig. 5a). The difference was 3.3 W/

**Table 1 Cases for the measurements and temperatures in the chamber**

| Name of cooling device | | REF (°C) | FANS (°C) | VEST (°C) | | |
|---|---|---|---|---|---|---|
| Name of cases | | | | PCM | ICE | PCM + ICE |
| Surrounding temp. [1.1 m] | Average* | 24.9 | 24.9 | 31.2 | 31.3 | 30.9 |
| | Highest | 25.0 | 25.3 | 31.3 | 31.5 | 31.0 |
| | Lowest | 24.8 | 24.8 | 31.0 | 31.2 | 30.8 |
| Max. vertical temp. difference [1.7–0.1 m] | | 0.7 | 0.7 | 0.7 | 0.7 | 0.5 |

* Average periods were 3 h for fan and 4 h for VEST

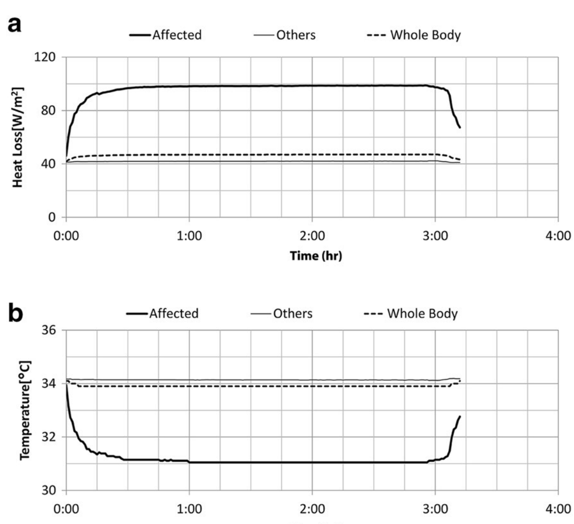


**Fig. 5** Measurement result of FANS. **a** Heat loss, **b** temperature

$m^2$. After 2 h, they were 98.7 $W/m^2$ in affected segments and 42.1 $W/m^2$ in the other area. The difference was 46.6 $W/m^2$. But the values for the whole body were 42.9 and 47.0 $W/m^2$. The increment was 4.1 $W/m^2$. The total area of the face and the scull was 0.13 $m^2$, which was less than 10% of the surface area. The local cooling effect by FANS was large and constant for 3 h but the effect for whole body became relatively small. The temperature at the affected segments was 33.9 °C at the beginning and 31.0 °C after 2 h (Fig. 5b). The temperature decrease was 2.9 °C. The temperature distribution between affected segments was 1.4 °C at the beginning and 0.9 °C after 2 h.

The clothing insulation was calculated from the average value of the last 60 min. It was 0.75 clo for REF and 0.48 clo for FANS. The Heat losses for each segment were shown in

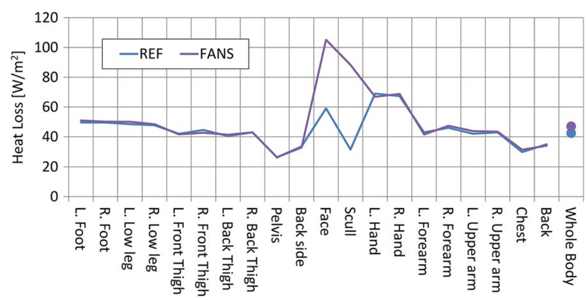


**Fig. 6** Heat loss distribution among segments of FANS

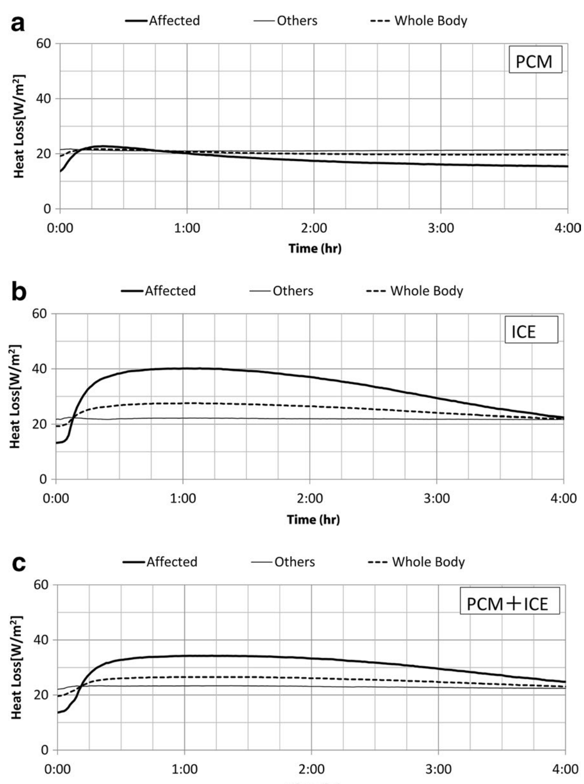


**Fig. 7** Heat loss of VEST. **a** PCM, **b** ICE, **c** PCM + ICE

Fig. 6. The difference was only seen in the face and the scull. The face had larger heat loss than the scull because the scull is covered by helmet. But the increments by FAN were 44.1 W/m$^2$ for the face and 56.9 W/m$^2$ for the scull.

## Effect of VEST

The affected segments with VEST were pelvis, backside, chest and back. They were predictable because VEST covers only upper parts of the body. Figure 7 summarized the measured heat loss for 4 h after starting the measurements. In the view point of heat loss at affected segments, the peak values were 22.8 W/m$^2$ for PCM, 40.1 W/m$^2$ for ICE and 34.3 W/m$^2$ for PCM + ICE. The largest value was achieved by ICE because the inner surface temperatures of cooling bags in the pocket of VEST were the lowest among cases. This result is consistent with Gao et al. (2009). The peak values of heat loss for whole body were 21.7 W/m$^2$ for PCM, 27.5 W/m$^2$ for ICE and 27.6 W/m$^2$ for PCM + ICE. The increments of the values from the beginning were 2.5, 7.5 and 7.0 W/m$^2$ respectively.

The elapsed times for the peak were different according to cases. They were 20 min for PCM, 68 min for ICE and 69 min for PCM + ICE. The approximate periods for the peak were 4 min for PCM, 13 min for ICE and 28 min for PCM + ICE. The manikin had its characteristics and the phase change materials continued to melt after starting the measurements. The results were the combination of those two aspects. But it can be said that PCM itself had shorter endurance than ICE. The combination of them brought the longest endurance among the measurement cases.

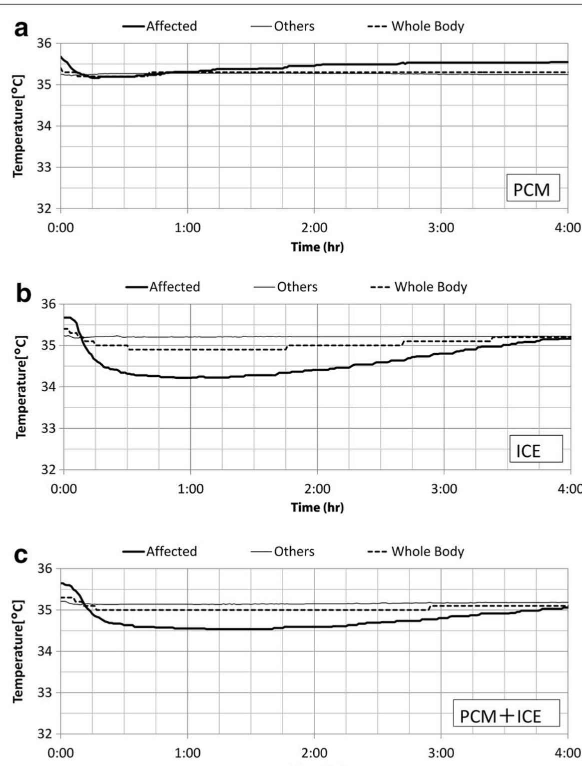


**Fig. 8** Temperature of VEST. **a** PCM, **b** ICE, **c** PCM + ICE

The temperature decrease of the affected segments at the peak of heat loss from the beginning were 0.5 °C for PCM, 1.5 °C for ICE and 1.1 °C for PCM + ICE (Fig. 8). The temperature distribution among affected segments was 0.0 or 0.1 °C for all cases at the beginning. They were 0.5 °C for PCM, 1.4 °C for ICE and 1.0 °C for PCM + ICE at the peak time. The larger the peak heat loss was, the larger the distribution at peak was.

## Discussion

In relation to endurance, FANS has almost constant effect for about 3 h, while the effect of VEST varies among the measurement cases and could last for about 30 min. There was no dew condensation in the measurement of VEST. The condensation will weaken its cooling power and will make the duration time shorter. The result of VEST have higher cooling power and longer duration time than the measurement in the condition with dew condensation. The working hours for outdoor workers are about 8 h. It is necessary to exchange batteries for FANS and cooling bags for VEST. Lu et al. (2015) evaluated a newly developed cooling device with cooling bags and cooling fans. There were two fans for upper body and two fans for lower body. 18 Cooling bags with a phase change material were for upper body and six bags for lower body. It reported that the cooling power of the cooling bags to whole body lasted for 78 min at longest and mentioned that the cooling effect depended on both of the mass of phase change material and the coverage area. Meanwhile, this study used water (ICE) and phase change material (PCM). The approximate periods for the peak were 4 min for PCM, 13 min for ICE and 28 min for PCM + ICE. The duration time depends on the mass of phase change materials and also depends on phase change materials itself which have different melting temperatures.

Lu et al. (2015) defined "cooling power" as the increase of heat loss from the steady state condition. This study uses the term as the increment of heat loss from the beginning. The cooling power of FAN was 4.1 W/m$^2$ for the whole body. The sensible heat loss of manikin was 47.0 W/m$^2$ and the ratio of the increment was about 9%. The cooling power of VEST was 7.5 W/m$^2$ at largest. The cooling power for sensible heat of FANS is larger than that of VEST in these measurements. FANS changes the convective heat transfer coefficient around the body, which affects the sensible heat loss and the latent heat loss from the human body. VEST cools down the body mainly by direct contact and it work for sensible heat loss. Considering the effect to latent heat loss, FANS is more effective than VEST. Beside the cooling power itself, the lasting periods of the peak value were about 180 min for FANS but about 30 min for VEST. Workers with VEST might have to change its cooling bags every half an hour, which is not realistic in construction sites. Contrary to VEST, workers with FANS only have to change batteries every 3 h. FANS have an advantage in practical point of view. But VEST has the effect of cooling down the body locally and directly. It may be useful for limited usage such as to the work with high surrounding temperature in the afternoon.

Zhao et al. (2013) reported that the zone where the fans were located was the best ventilated and cooled. This study observed local cooling powers for different manikin segments in consistency with that study. FANS had similar cooling power for the scull and the face. The power was about 50 W/m$^2$. It would be difficult to supply cooling power to these segments by cooling garments. VEST had different powers on different segments. The temperature distribution among affected segments was very small at the beginning but it became large at the peak. The larger the peak heat loss was, the larger the distribution at peak was. The cooling power to the face and the scull by FANS and the resulted temperature distribution among affected segments by VEST are the features of these cooling devices. Besides, the weight of FANS is 700 g and that of VEST is 2.5 kg with 22 cooling bags. The heavier the devise is, the more interactive with job performance the device is. Chan et al. (2015) reported that the survey in construction industry gave the lowest score of subjective perception for a cooling device. Subjective evaluation by workers is necessary for these aspects.

This study evaluates the nominal clothing insulation of FANS. But clothing insulation itself cannot explain the effect to evaporative heat loss. FANS realizes high convective heat transfer coefficient around the body and the effect to the evaporative heat loss should be evaluated. The simulation model for SET includes the effect of evaporative heat loss, which changes according to clothing insulation (Gagge et al. 1986). The effect of FANS is evaluated by SET. A worker is supposed to work with pick and shovel work (4.0 met) under sunshade (ASHRAE 2013). The radiant temperature is the same as the air temperature. The relative humidity is 50% and the wind velocity is 0.5 m/s. Figure 9 shows the SET with two kinds of clothing according to the surrounding temperature. The SETs for REF (0.75 clo) and FANS (0.48 clo) at 35 °C of the surrounding temperature are 39.9 and 37.3 °C respectively. The difference between them is 2.6 °C. The lower the surrounding temperature is, the larger the difference between SETs of different clothing insulation value is.

## Conclusions

Two kinds of wearable cooling devices were evaluated for their cooling effect by a thermal manikin in the view point of utilization for construction industry. The cooling fans (FANS) mainly cooled down the face and the scull, bare part of the body, and increased the heat loss for the whole body about 9%. The cooling power continued for about 3 h. They also decrease the clothing insulation from 0.75 clo of the reference to 0.48 clo. The cooling vest (VEST) for heat protective clothing has smaller cooling effect than FANS and the peak cooling powers continued for about 30 min. The effect of FANS to SET is evaluated by simulation. The difference of SET between REF and FANS at the surrounding temperature of 35 is 2.6 °C.

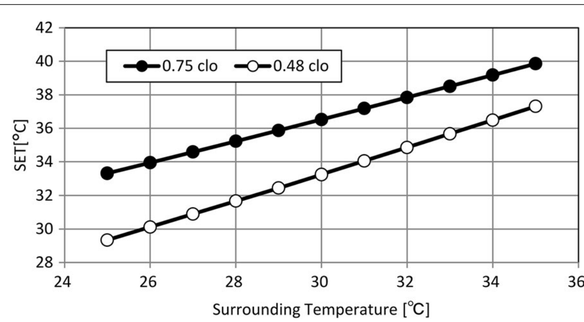


**Fig. 9** Difference of SET by FANS

**Authors' contributions**
All authors contributed to all phases of this research. All authors read and approved the final manuscript.

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**Competing interests**
The authors did not receive any funding to this research. The authors declare that they have no competing interests.

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